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Digitizer Architecture Analysis for Target Diagnostics on the National Ignition Facility

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SUMMARY

This paper covers a systems engineering analysis of existing scope-based Target Diagnostics (TD) on the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL), for the purpose of selecting a standard digitizer architecture future diagnostics. Key performance criteria and a summary of test results are presented.

Currently of the 60+ Target Diagnostics, at least fifteen use a type of high speed electrical signal data read-out device leading to over 200 digitization channels spread over six types of CRT and digital oscilloscopes, each with multiple models and versions. The proposed standard architecture discussed in this paper allows the NIF to efficiently and reliably operate digitizers that meet the required performance metrics for the lifetime of the NIF.

The systems engineering analysis identifies key stakeholders for multiple subsets of scope-based diagnostics including but not limited to the nToFs (neutron Time of Flight), DANTE a broadband, time-resolved x-ray spectrometer, SPBT (South Pole Bang Time), GRH (Gamma Reaction History), and FFLEX (Filter Fluorescer Diagnostic). From these stakeholders, key performance metrics are derived and feed into test and evaluation criteria for different digitizers and architectures.

Keywords: NIF, Target Diagnostics, Systems Engineering, Digitizer,

1. INTRODUCTION

The National Ignition Facility is the largest high energy density science facility in the world. Currently of the 60+ Target Diagnostics, at least fifteen use a type of high speed electrical signal data read-out device leading to over 200 digitization channels spread over six types of CRT (Cathode Ray Tube) and digital oscilloscopes, each with multiple models and versions. Every diagnostic is designed to measure a specific physical phenomenon resulting in different requirements for each digitizer. Though there has been some effort to use standardized readout architecture this formal system engineering analysis yields benefits for new systems and upgrades to existing diagnostics. Some of these benefits include reduced initial build cost, operational efficiency, reducing consumed rack space, reducing rack heat loading, planning for common spares, improving reliability, improving data quality, and reducing long term operational costs.

The NIF became an operational science facility in 2009 and was designed to have at least a 30 year operational lifetime. If a typical life cycle for a digitizer is 3 years of sales and an additional 5 years of manufacturer support, then in order to keep NIF diagnostics using state of the art, manufacturer supported, digitizers they will all need to be replaced three times over the life of the project. If a typical digitizer channel cost is between $10k and $40k the long term cost to the facility will be a substantial. The benefits from a common digitizer architecture developed from a system engineering analysis can have a lasting impact on the success of NIF.

The conclusion of this systems engineering analysis is that there should be a total of three all digital architectures for all upgrades and future diagnostics based primarily on two parameters, bandwidth and channel count. Additionally, the use of channel input circuits (protection and/or signal modification) is needed and will be implemented to maintain the current reliability standard and allow for the transition away from CRT based oscilloscopes.

The author acknowledges that future systems may have unique requirements that cannot easily follow the process outlined here. Additionally, changing commercially available technology may change the results of this analysis. Each new diagnostic or upgrade should undergo a systems engineering analysis to determine the proper requirements and determine if this architecture will meet the requirements. This analysis should be updated on a periodic basis (every 3-5 years) or whenever significant new digitizers come onto the market.

2. SYSTEMS ENGINEERING ANALYSIS

2.1 Mission, Scope, Objectives, Goals, and Needs

The mission of this analysis is to develop a flexible digitizer implementation that will save rack space provide a standard architecture for future diagnostics. The approach taken was to analyze existing TD systems to inform future designs. System that were included in the analysis are the nTOFs, DANTE, SPBT, GRH, FFLEX, FABS, NBI, EMP, SGEMP and DIM based framing camera pulse monitors. Performing analysis on fully operational "mature" systems allows for a more complete understanding of the initial needs and how they changed as the system evolved. This document is not intended to address the specific needs of any single system instead it layouts a guide for future diagnostics to leverage during their conceptual design and requirements phases.

Currently digitizers used in NIF are large, expensive, do not scale well and some require frequent repairs and calibration. Target Diagnostics needs a plan for addressing the needs of new diagnostics while maintaining the functionality of existing systems over the 30 year lifetime of the NIF. This systems engineering analysis lays out the current needs, solutions, and a preliminary set of tests to determine the best implementation of this solution.

2.2 Context Diagram

Digitizers constitute a small part of a typical target diagnostic system. A context diagram for a typical diagnostic system is shown in Figure 1, with both active and passive stakeholders. One objective for new system architecture is to removed or minimize routine interaction with the system by operators. The context diagram in Figure 1shows, TDOs (Target Diagnostic Operators), maintenance, and the RSE (Responsible System Engineer) interacting with the system however this is not a daily interaction.

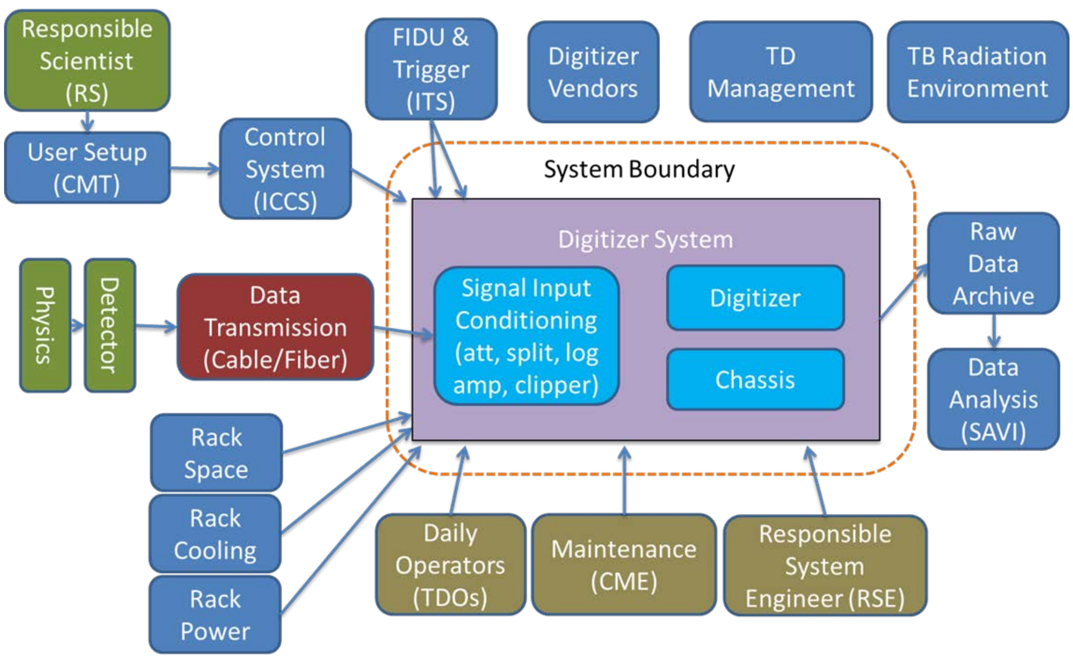

Figure 1. Digitizer System Context Diagram: This shows all the active and passive stakeholders. Stakeholders that have arrows that cross the system boundary are active stakeholders that directly interact with the system. Passive stakeholders do no directly interact with the system however they are also used to generate the key expectations.

At the most fundamental level the purpose of a target diagnostic is to measure a physical parameter. The context diagram in Figure 1, shows the data path, starting with the physical parameter that needs to be measured, then it is detected and turned into an electrical signal in the detector/transducer, passed down a data transmission system, where it then it enters the system boundary. In current system architecture the only component in the digitizer system is the oscilloscope. The proposed architecture shown in the context diagram consists of three components with some implementations having only one or two of these elements depending on specific diagnostic requirements. Every system will have a digitizers, if many channels are needed this digitizer will be a card placed in a chassis. If there is a need to protect the digitizer due to the potential for damaging signals an input conditioning circuit will be installed. After the data is analyzed it is passed to the data archive where it can be analyzed by automated software analysis or by the RS. The RS then can use this data to determine what settings may need to be changed for the next experiment and setup the diagnostic using software tools and the process starts all over again when the next NIF shot fires.

2.3 Stakeholders

From the context diagram active and passive stakeholders were determined. These stakeholders are listed in Table 1. They were then ranked based on the impact to the success of the diagnostic system. The ranking allows for prioritization of expectations and resolves conflicting expectations.

Rank	Role	Active or Passive
1	TD Management	Passive
2	Responsible Scientist (RS)	Passive
3	Nature/Physics	Passive
4	Responsible System Engineer (RSE)	Active
5	Maintenance	Active
6	Detector & Transducer	Passive
7	Racks (Space, heat load, and power)	Active
8	Digitizer Vendors	Passive
9	Data Transmission System	Active
10	FIDU and Trigger System (ITS)	Active
11	Control Systems (ICCS/TD IBCs)	Active
12	Target Diagnostic Operators (TDOs)	Active
13	Data Analysis Systems (Archive Viewer)	Passive
14	Shot Setup (CMT)	Passive
15	TB Radiation Environment	Passive
16	Data Archive	Active

Table 1. Key Stakeholders for Target Diagnostic Digitizer Systems: These stakeholders are ranked on how much impact they have on the success of the system. Active Stakeholders directly interact with the system while passive stakeholders do not.

Twelve stakeholder interviews were conducted. Individuals were interviewed based on their roll and system they are familiar with. Because some stakeholders are systems, not people, individuals responsible for those systems were interviewed wherever possible. Diagnostic Responsible Scientists (RS) and Responsible System Engineer (RSE) for several diagnostics including the nToFs (neutron Time of Flight), DANTE a broadband, time-resolved x-ray spectrometer, SPBT (South Pole Bang Time), GRH (Gamma Reaction History), and FFLEX (Filter Fluoresce Diagnostic) were interviewed. Group leaders for NIF controls systems, timing system, diagnostic systems, maintenance groups, and management were also interviewed.

Stakeholders were interviewed individually whenever possible. During each interview the stakeholder heard the same set of questions acknowledging that some questions may not apply. By covering the same set of question with every stakeholder they were given an opportunity to add insight to the system from outside of their primary roll. The questions were designed to guide the conversation; the objective was to allow the stakeholder to speak freely about their needs without focusing on low level details.

The interview questions are listed below:

- Describe what you are trying to measure.
- Describe how fast this happens or how fast it is driven.
- Distinguish subsystems or subgroups that measure this currently.
- How does this become electrical? Specifically, what is the performance of the transducer?
- Describe what you don't like about your current digitizer system.
- Describe what you do like about you current digitizer system.
- If you had it to do over again what would you do differently?
- What are your top 3 requirements or more generally expectations from your point of view?

2.4 Key Expectations

The top three key expectations from each interview were analyzed along with general comments about digitizer performance, likes, dislikes, and opinions about how an individual would do it over again. These key expectations are listed in Table 2. Although it was not explicitly stated in most interviews the most important expectations is that any new (or replacement) system would not compromise the performance the system currently has. This subtle point cannot be overlooked. If performance was to be reduced to meet other key expectations it is likely that key stakeholders such as the Responsible Scientist would not accept the new design.

These key expectations or key acceptance criteria represent high level requirements that if no met result in a failure of the system or project.

Rank	Key Expectation	Capability or Characteristic
1	Digitizers must have performance characteristics equal to or greater than the existing options	Capability
2	Digitizers architecture must be planned to meet the needs of the facility for the next 30 years	Capability
3	Digitizers should be as reliable as possible	Characteristic
4	Minimize the rack space and heat load	Characteristic
5	Minimize maintenance and calibration needs	Characteristic
6	Minimize the number of different types of digitizers (canned solution for future applications)	Characteristic
7	Digitizer must be commercially available	Characteristic

Table 2. Key Expectations: These expectations or key acceptance criteria are ranked in importance to success of the diagnostic. If these critical capabilities or characteristics are not met the design may be considered a failure.

Goal expectations were also gathered. These expiations may not be met however every reasonable effort will be made to achieve them. They are listed below

- Obtain a single digitizer that can be used in all current and future applications
- Minimize cost per digitizer channel
- Minimize the cost per ENOB (effective number of bits)
- Digitizers should be scalable (able to build a small channel count or large easily)
- Greater than 8 ENOB @1GHz

3. OPERATIONAL ARCHITECTURES

3.1 Summary Existing Architecture

Currently there are two types of digitizers implemented in NIF Target Diagnostics, CRT oscilloscopes and digital oscilloscopes. There are two types of CRT oscilloscopes, obsolete Tektronix SCD5000 and Greenfield FTD10000 (see Top Right of Figure 2). All of the digital oscilloscopes are from Tektronix. Lower bandwidth versions are all DPO7000 series with bandwidths of 1GHz, 2 GHz, and 2.5GHz (see Top Left of Figure 2). Higher bandwidth scopes are all DPO70000 series with bandwidths of 6GHz and 12.5GHz (versions A, B, and C with and without 2SR enhanced sample rate option, see Bottom Right of Figure 2). To increase dynamic range dividing a single detector output on to multiple oscilloscope channels with different vertical scales is a common practice[1]. Splitting signals over multiple channels increases dynamic range and depending on how it is implemented increases the ENOB for a system. All older TDS series scopes have been phased out due to issues with their time base.

Due to the high radiation environment in the target bay (TB) during shots, digitizers are kept in rooms called diagnostics mezzanines outside of the TB. Typical lower bandwidth applications utilizes a single large TimesMicrowave LMR600 or similar coaxial cable run from the detector to the oscilloscope where the input is spread over multiple channels to increase the dynamic range and SNR. Line insertable attenuators splitters and FIDU signals are all mixed in at the oscilloscopes. This cable run ranges from 100’ to 200’ depending on the detector location, conduit/ cable tray availability, and rack space.

Systems requiring higher bandwidth utilize a series of O/E converters to change an optical signal typically generated by a Mach-Zhender Modulator close to the detector[2]. Additional rack space for the O/E is required. The DPO71254 shown below typically consumes over 400W continuously and internal temperature in the racks where multiple scopes are mounted can exceed 40C.

Tube based digitizers including the Greenfield FTD10000 and the Tektronix SCD5000 are utilized due to their large dynamic range, insensitivity to over voltage conditions, and fast recovery after an over voltage condition. The FTD10000 occupies less rack space than a SCD5000s however they are both single channel devices requiring frequent time base calibration. Additionally they have none of the typical front panel functionally that digital scopes have. FTD10000s have a limited record length that requires operators to manually install and remove FIDU optical delay spools from shot to shot. Both tube base digitizers have relatively poor reliability records in NIF.

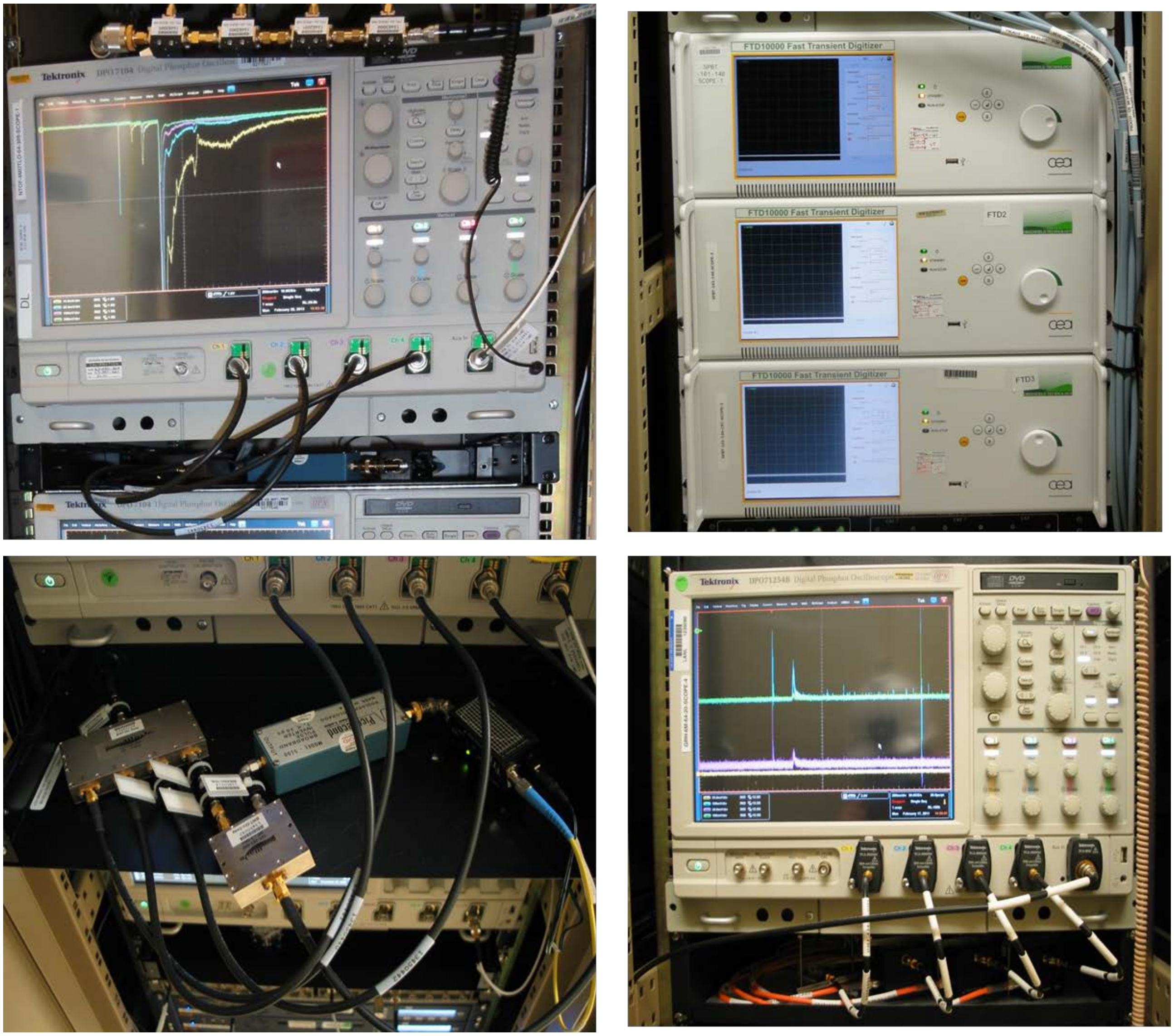

Figure 2. These images show digitizer configurations in NIF TD. Top Left: nTOF DPO7104 scope, Top Right: SPBT FTD1000s, Bottom Left: nTOF Signal splitters and FIDU mixing, Bottom Right: GRH DPO71254 with O/E converters.

3.2 Summary of Commercially Available Digitizers

A key expectation is the commercial availability of the digitizer. The following sections break down the possible digitizer form factors into several categories, chassis based, oscilloscopes, standalone units, and low profile digitizers. Initial work has concluded that NIF can benefit from compact ADCs[3]. The units evaluated do not constitute a complete list of all digitizers available but they represent a sample of what is commercially available at the time of this paper. As much information on each model was gathered from data sheets and papers. Parameters such as bandwidth, sample rate, record length, bits, ENOB, noise floor, input range, and required rack space, were used to categorize and evaluate each option. The survey of commercially available digitizers was used to develop an architecture that meets all the key expectations.

3.2.1 Chassis Based Digitizers

Chassis based digitizers standards for high precision and/or high channel count include VME, PXI, and AXI. NIM Crate options have been excluded due to the lack of available and relative age of this backplane/chassis technology.

VMEbus is a computer bus standard, widely used for many applications and standardized by the IEC as ANSI/IEEE 1014-1987. It dates back to 1979 and is fairly ubiquities. Many Front End Processors (FEPs) in NIF for other systems use VME chassis and cards. Contending VME based digitizers evaluated in this analysis include U1083A-002 Acqiris SVM1500, CAEN (Costruzioni Apparecchiature Elettroniche Nucleari S.p.A) models V1742, V1743, VX1742, VX1743, V1761, and VX176, and Acquitek/Struck SIS3305.

PXI is a modular instrumentation platform originally introduced in 1997 by National Instruments based on CompactPCI. PXI is promoted by the 54-member PXI Systems Alliance. Over a thousand modules for a variety of purposes are available. Typical chassis are 4U high and can contain up to 18 modules. Contending PXI/PXIe models evaluated in this analysis include Keysight M9210A and M9211A, and National Instruments PXIe-5186, PXIe-5185, PXIe-5162, and PXIe-5160.

AXIe is a modular instrumentation standard created by Aeroflex, Agilent Technologies, and Test Evolution Corporation. AXIe was launched in 2009 it is a fairly new standard that offers some advantages over PXI yet it does not have as many modules and instruments available. Contending AXI models evaluated in this analysis include Keysight M9703 and the Guzik ADC 6000 Series.

3.2.2 Standard multi-channel digital Oscilloscopes

Oscilloscopes from Tektronix, Keysight (formally Agilent), Teledyne LeCroy, Rohde-Schwarz were all evaluated. Tektronix DPO7000 and DPO70000 series digitizers are widely used and trusted in NIF target diagnostics. Significant testing has been conducted on overdrive conditions, time base, linearity, and inter channel timing.

Keysight oscilloscopes including the Infiniium DSO90000 DSAZ, DSOZ, DSOX3104T, and the S-Series DSO High-Definition Oscilloscope were evaluated. The S-Series DSO scopes were released during this analysis and have shown very promising results.

Teledyne LeCroy oscilloscopes including WaveSurfer 10, HDO4000, WaveRunner 6 Zi, HDO6000, HDO8000, WaveMaster 8 Zi-A, and LabMaster 9 Zi, LabMaster 10 Zi Modular Oscilloscopes were evaluated. The largest advantage noted in these oscilloscopes was in the modular high bandwidth oscilloscopes. Applications requiring many high bandwidth (>6GHz) channels may benefit from these models. Rohde-Schwarz models R&S RTO1044, RTO1024, RTO1014, and RTO1004 were also evaluated.

3.2.3 Standalone Compact Digitizers

Standalone bench top digitizers such as the Picoscope 6507 were also evaluated. Several VME digitizers from CAEN are offered as bench top version, these include models DT5742, DT5743 and, DT5761. Similarly, Guzik offers a bench top SGA 6000, a bench top version of their AXI ADC6000. These bench top version offer smaller form factor without the need for a full chassis if fewer channels are needed.

3.2.4 Low Profile/High Channel Density Oscilloscopes and Digitizers

Low profile digitizers are very desirable for rack based systems that typically do not have individuals interacting with the front panel of the oscilloscope on a regular basis. The idea of removing the screen controls, and other nonessential components would leave a low profile "pizza box" digitizer with identical performance to the scope it was based on. Unfortunately this market for these low profile digitizers is small so very view scopes have been turned into low profile digitizers. A notable exception is the Keysight DSO90008 Series low profile oscilloscope/digitizer. This was evaluated along with the Keysight DSO90808A Infiniium, Greenfield GFT6012 and GTF6022.

3.3 Proposed Digitizer Architecture

When examining the digitizers that are currently deployed in NIF it is clear there are two architectures, a digital scope or a tube based digitizer. Similarly, no single digitizer architecture can meet all the key expectations, there for a minimum set of three high level architectures is proposed. The Pugh Charts in Table 3 shows how each technology category ranked against the key expectations. Specific models were not chosen for each architecture however evaluation criteria was derived and is shown in section 4.1.

Architectural Option #1 covers the high precision, and dynamic range (higher ENOB), high channel count (>16 channels), and relatively low bandwidth (<1GHz) needs. This is best implemented using a chassis based digitizer due to the high channel count with a minimum amount of rack space consumed. This architecture allows for individual cards to be replaced as they become commercially available while utilizing existing chassis that typically last much longer (similar product cycle to a backplane).

Architectural Option #2 covers the high bandwidth (>6GHz) needs. Currently the only commercially available digitizers that can digitize 6- 45GHz bandwidth signals are lab grade oscilloscopes.

Architectural Option #3 covers the high precision, and dynamic range (higher ENOB), medium channel count (4-16 channels), and medium bandwidth (1-8GHz) needs. Currently chassis based digitizers do not have the bandwidth, sample rate, or ENOB combination that allows for their use in this category. Oscilloscopes are recommended for these applications.

The selection of a digitizer architecture should be driven by the individual needs of each system. At the conceptual design stage an estimates of the total channel count, bandwidth, and dynamic range/precision could be compared with these three options summarized in Figure 3. There is intentional overlap between options that allows the best architecture to be selected to meet the needs of the specific system.

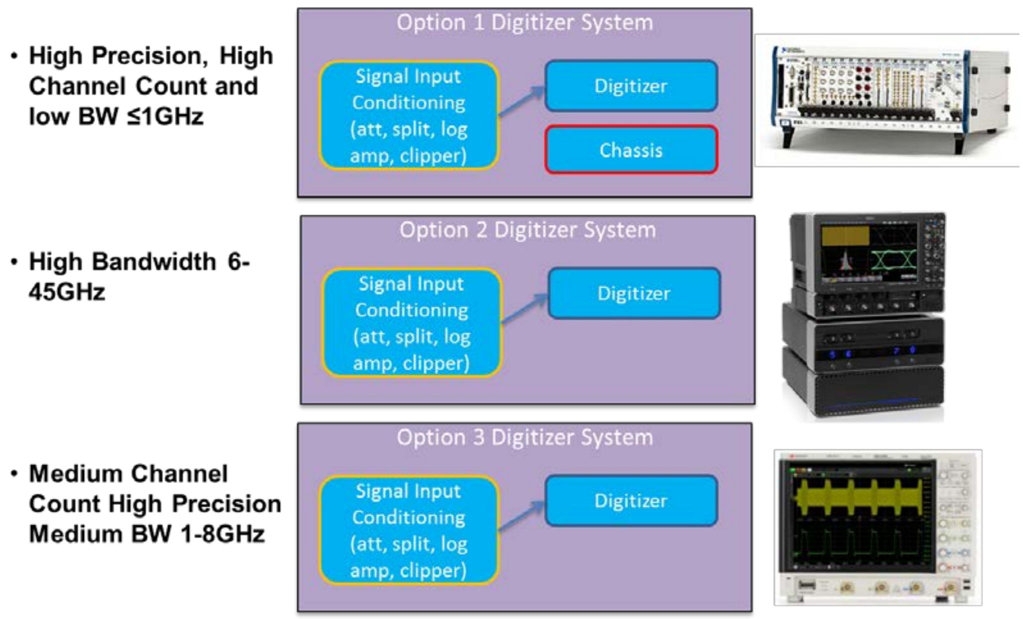

Figure 3. The Three Architectures: Option #1 is high precision, high channel count, and low bandwidth. Option #2 is high bandwidth and Option #3 is high precision, medium bandwidth, and medium channel count.

3.4 Application Driven Digitizer Selection

One of the objectives of this analysis was to develop a standard architecture for future diagnostics. This is best implemented using three options based on key performance parameters system bandwidth, dynamic range total, and channel count. Accurate and early determination of the key digitizer performance requirements for an upgrade or new diagnostics in conjunction with the decision tree and decision cloud below simplify and shorten the design process.

The decision tree and cloud (Figure 4) were created to aid in determining the best architecture to use for a given application. The decision tree starts with determining the needed digitizer bandwidth. If the bandwidth required is likely greater than 6GHz a digital oscilloscope is the best option regardless of the dynamic range or number of channels. The survey of commercially available digitizers does not have many high bandwidth digitizers that are not oscilloscopes. If the bandwidth is in the range of 1GHz to 8GHz and the channel count is under 25 the best option is a medium bandwidth oscilloscope. In order to increase dynamic range 10 bit oscilloscopes are recommended in this category. If the channel count is very large ie greater than 16 channels and the bandwidth requirements are relatively less than 1.5GHz a digitizer chassis is the best option.

There are regions where channel count and bandwidth can lead to multiple two options. In these regions further analysis of the performance characteristics of the system must be known and both options should be evaluated through the design process. It is possible to have more than one solution that meets all the key expectations.

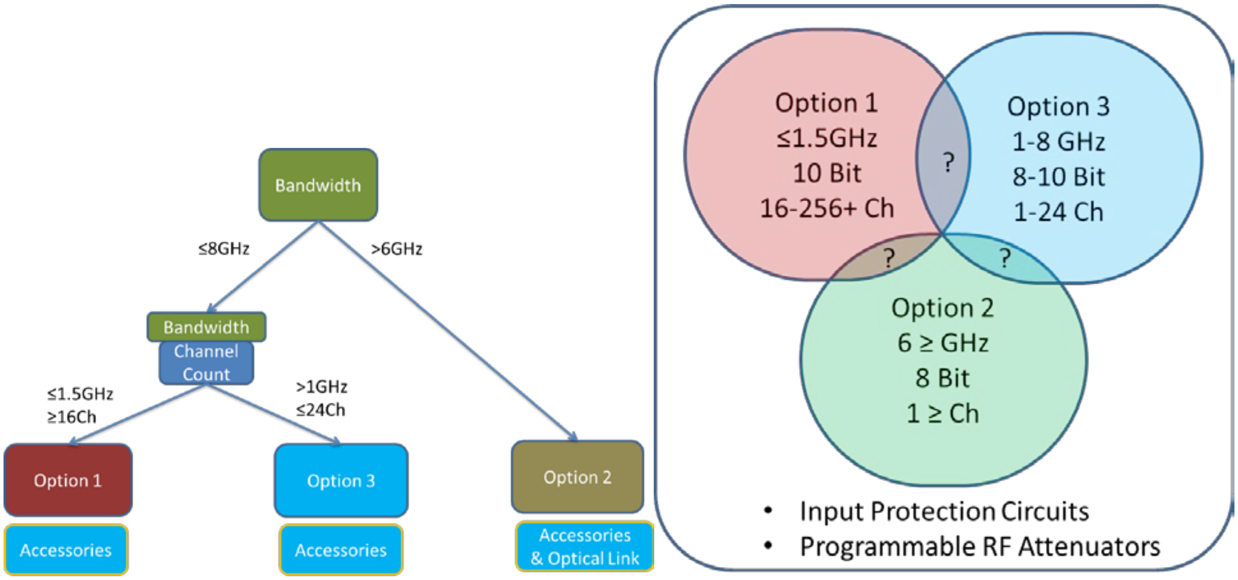

Figure 4. A decision tree (left) and a decision cloud (right) should be used to determining the primary architecture to investigate for a new or upgraded diagnostic during the conceptual design phase. The overlapping regions represent areas where both architectures should be investigated and further system requirements are needed.

3.5 Input Protection and Signal Modification

An input protection clipper circuit is necessary for all proposed solutions. This simple a passive element that senses an over voltage condition and provides a path to ground. In the case of fast transient signals like those experienced by diagnostics on NIF this circuit must react fast enough to protect in sensitive input of a high speed digitizer. The reaction time will be function of how the clipper circuit is designed. The clipper circuit may be as simple as a Shottky Barrier Diode or may be an active circuit with a sensing node, delay line, and RF transistors. The design of the clipper circuit should be subject of an additional systems engineering analysis to determine the proper requirements and architecture. For the purposes of this document it is assumed that such a protection circuit can be assembled to protect the input electronics of digitizers from expected overvoltage conditions. It is not necessarily expected that data could be recorded after the clipper circuit has activated.

High Speed Solid State RF Switches in conjunction with delay lines can be timed with the signal of interested input to allow data channels be turned on and off to allowing improved SNR at different points in the waveform. Gallium Nitride (GaN) transistors with switching times in the Sub-nanosecond timeframe are commercially available.

Log-Amps, Log-Attenuator, and Signal Compressors are another option for signal modification and protection. Many of the signals observed in NIF are typically analyzed and displayed on logarithmic scales. Unfortunately most digitizers are set up to measure voltages in a linear manner. The concept of altering the input to record it in a logarithmic matter following a well-defined and repeatable manner is not unique to this field companies such as Pasternack make logarithmic amplifiers (FBLA-0.1/1-70BC 10MHz to 1GHz). Further analysis into the possible application of such a compressor will be explored in future work.

An Eletro Optical modulator such as a Mach-Zehnder in conjuction with an Optical to Electrical converter can also be used to protect the sensitive front end inputs of digital oscilloscopes as well as increase dynamic range while maintaining high bandwidths[4].

3.6 Comparison of Proposed vs. Current Digitizer Architecture

The Pugh chart in Table 3 shows the different possible architectures ranked against the key expectations. The current architecture consisting of vacuum tube and digital oscilloscopes scored lower than the others largely due to the drawbacks of the vacuum tube based FTD1000s and SCD5000s. Any all-digital architecture with the proper implementation of input protection and programmable attenuators will be an improvement over the current implementation.

Options two and three are combined into a general title of "Many Digital Scopes" and option one is titled "Chassis Based Digitizers. Using these three architectures all key expectations can be met.

Key Expectation	Relative Weight (1-4)	Chassis Based Digitizer [#1] (w/Accessories)	Many Digital Scopes [2 &3] (w/Accessories)	Stand Alone Compact Units (w/Accessories)	Low Profile Digitizers (w/Accessories)	Current Deployment (Tube and Digital)
Performance	4	4	4	2	1	4
30 year Plan	2	4	2	2	2	1
Reliability	2	3	4	3	3	1
Rack space	3	4	1	4	4	1
maintenance and calibration needs	1	4	4	4	4	1
# Of Versions	1	3	3	2	3	1
Commercially Available	4	4	4	4	4	2
Totals (Higher is Better):	68 points possible	65	54	52	49	33

Table 3. This Pugh Chart rates possible digitizer architectures against the weighted key expectations.

Further analysis into the best chassis based digitizer for option one is underway; current work is focusing on PXI/PXIe and AXIe. Medium bandwidth scopes for use in option two are also being evaluated; currently this work has focused on Keysight S-Series and Tektronix DPO7000 series scopes.

3.7 QFD (Quality, Functional Deployment)

The high level QFD (Table 4) shows the highest correlation between the key expectations and a quantifiable digitizer characteristic. This is used to determine testable performance metrics (TPMs) and guide the priority of requirements for a specific system. The most highly correlated parameter was cost per ENOB. This means that focusing on a solution that optimizes the cost per effective number of bits is most likely to yield the largest benefits to all the key expectations. A digitizer that has more ENOB will likely require fewer channels, to cover the needed dynamic range leading to less consumed rack space, fewer components needing calibration and maintenance and lower overall cost to operate. Two characteristics tied for the second spot including bandwidth and maintainability. It is unsurprising that a performance metric such as bandwidth is highly correlated with all the key expectations. Maintainability ie the cost of calibrating and repairing the system clearly impact almost all of the key expectations.

	Relative Weight (1-9)	Occupied Rack Space (how many U taken per channel)	Scalability (How many channels can be added)	How much new NIF Software is needed to be developed	Reliability (MTBF and MTTR)	Maintainability (how often is calibration required)	User interface (how easy is it to troubleshoot)	Vendor Supported Lifecycle (years produced and years suppored)	Cost Per Channel and ENOB (ENOB may reduce number of channels needed)	Effective Number of Bits (ENOB)	Record Length (ns of data recorded)	Sample Rate (Gsa/s)	Full Scale Range input voltage and adjustability	Vendor Supplied Software Functions (DSP, measurements, adjustment)	Bandwidth (GHz)	Vendor's Reputation (support, reliability, legacy)	Technology maturity (years and number of vendors involved)	Dynamic Range (single shot and shot to shot)	Signal to noise and Distortion (SNRD)
Performance	9	0	1	0	1	3	0	1	9	9	3	9	3	3	9	1	3	9	9
30 year Plan	3	9	9	1	9	9	1	9	3	0	0	0	0	0	0	3	3	0	0
Reliability	3	0	0	0	9	9	0	9	3	0	0	0	0	0	0	3	9	1	0
Rack space	7	9	9	0	1	0	9	0	3	0	0	0	0	0	9	0	3	1	1
maintenance and calibration needs	1	0	0	0	9	9	1	9	3	0	0	0	0	3	0	3	0	0	0
# Of Versions	1	3	3	9	9	9	1	9	1	1	0	1	1	3	9	0	0	0	0
Commercially Available	9	9	9	1	9	9	3	9	9	0	0	0	0	0	3	1	1	1	1
Weighted Total:		**174**	**183**	**21**	**169**	**180**	**95**	**162**	**205**	**82**	**27**	**82**	**28**	**33**	**180**	**39**	**93**	**100**	**97**
Highly Correlated Ranking		**3**			**4**	**2**		**5**	**1**						**2**				

Table 4. Quality Functional Deployment (QFD) Diagram shows the correlation between testable performance metrics and key expectations.

4. DIGITIZER PERFORMANCE METRICS AND COMPARISON

One of the major objectives of this systems engineering analysis was to determine a set of performance metrics that can be used as a reference for future designs. When a design team has determined their requirements they can down select a digitizer from a list based upon this set of criteria.

4.1 Digitizer Evaluation Criteria

The following list of TPMs was derived from the stakeholder interviews and the QFD. This list represents the metrics a digitizer will be evaluated on. Once all the information is gathered and ranked the best option for a given architecture will be chosen. Much of this information is not provided and in some cases not known by vendors. These parameters will require testing.

- Specified Bandwidth
- ENOB @1GHz
- ENOB @2.5GHz
- ENOB @max BW
- Record length (total number of samples)
- SNDR (single shot)
- Noise Floor (this is a table it's different for each v/div)
- Time base stability
- Channel to channel Jitter (card to card and external trig to channel jitter as well, also multi-scope/chassis sync/jitter)
- DC Gain Accuracy
- AC Gain Accuracy @1GHz (S21)
- Overdrive Recovery Time (characteristics while overdriven, internal clipper, reflection amplitude)
- Overvoltage Input Damage threshold for a short pulse, RMS power (peak voltage and total watts delivered)
- Channel to Channel Crosstalk
- Input voltage range and adjustment

- Input voltage offset range
- Sample Rate
- Input Impedance over bandwidth
- Number of channels
- Number of channels at a given sample rate (or maximum)
- Rack space per channel
- Maximum number of cards in chassis if applicable (any additional power/cooling limits)
- Maximum number of channels in digitizer card
- Calibration Requirements (frequency and equipment)
- Cost per channel
- Cost per ENOB
- Product lifecycle duration (for sale and supported after)
- Produce warranty and warranty extension options
- Sparing plan Integration (one model that can be used in multiple deployments)
- Any tools to help validate system signal integrity built in (cable compensation)
- Type of software/hardware filtering is implemented (access to raw data? Brick wall? Gaussian?)
- Access to raw digitizer output (no software filters)
- Heat load for rack

4.2 Performance Comparison Data

A partial list of these parameters has is shown in Table 5. A complete list of performance results for a subset of digitizers is underway.

Equipment type	Brand	Part#	Bandwidth	# of Ch	Samples per second		Resolution in # of Bits		Rack Space	Max input voltage	record length	Comms	rise time (ps)
Pizza box	Greenfield	GFT6012	3GHz	1	10GS/s	1.00E+10	10	bits	1U	1	1.00E-02	Ethernet	
Pizza box	Greenfield	GFT6022	2.8GHz	1	3.6GS/s	3.60E+09	12	bits	1U	1	2.80E-06	USB	
CRT	Greenfield	FTD10000	5GHz	1	5 - 1000GS/s (10 bits)		13	bits	4U	2kV	2.00E-07	Ethernet	50
Digitizing Scope	Tek	DPO5204B	2GHz	2	10GS/s	1.00E+10	10	bits	5U	5 (RMS)	2.50E-03	Ethernet	175
Digitizing Scope	Tek	DPO4104B	1GHz	4	5GS/s	5.00E+09	8	bits	5U	5 (RMS)	4.00E-03	Ethernet	350
Digitizing Scope	Tek	DPO7354C	3.5GHz	4	10GS/s	1.00E+10	6	efbits	7U	5 (RMS)	2.50E-03	Ethernet	160
Digitizing Scope	Teledyne Lecroy	WaveRunner 620Zi	2GHz										
Digitizing Scope	Keysite	DSO9254A	2.5GHz	4	20GS/s	2.00E+10	8	bits	8U	5 (RMS)	5.00E-04	Ethernet	140
Digitizing Scope	Keysite	DSOSS254A	2.5GHz	4	10GS/s (20GS/sec/2 chnls)	1.00E+10	8	ebits (10bit ADC)	8U (2ea back to back)	5 (50ohm)	5.00E-03	Ethernet	108

Digitizing Scope	Keysite	DSOS404A	4Ghz	4	10GS/s (20GS/sec/2 chnls)	1.00E+10	7	ebits (10bit ADC)	8U (2ea back to back)	5 (50ohm)	5.00E-03	Ethernet	108
digitizer	Keysite	U5130	4GHz	2	10GS/s (5GS/sec/2 chnls)	1.00E+10	7	efbits	4U	5 VDC	0.00E+00	Ethernet	
digitizer	Keysite	U1065A-001 DC222	2GHz	1	8GS/s	8.00E+09	5	efbits	6U	5 VDC	1.25E-01	Ethernet	
digitizer	GaGe	CorbaMax	1.5GHz	1	4GS/s	4.00E+09	8	bits	PCI	6 (RMS)	8.00E+00	PCI	
digitizer	NI	PXIe-5162	1.5GHz	1	5GS/s (1 chnl); 1.25Gs/s (4chnl)	5.00E+09	7	efbits	4U	5 V(peak)	2.00E-01	PXIe	320
digitizer	NI	PXIe-5186	5GHz	2	12.5GS/s	1.25E+10	6	efbits	4U	5 V(peak)	8.00E-02	PXIe	320
digitizer	Caen	761	1GHz		4GS/s	4.00E+09	10	bits	1U	1 Vpp	0.00E+00	USB	
PXI - Mux system	NI	PXI-2545 4x1 Mux	2.7Ghz	8	N/A				5U	30Vrms			

Table 5. Performance Comparison data for 17 digitizers

4.3 Dante Upgrade

Recent work at NIF has focused on upgrading the digitizers used on Lower Dante. Dante is a broadband, time-resolved X-ray spectrometers measuring the time-dependent soft X-ray power produced by the NIF lasers interacting with the hohlraum[5]. The system operates using 18 single channel SCD5000s that are no longer being manufactured. The Dante upgrade started with a systems engineering analysis to determine the best digitizers for this application. Dante has required system bandwidth of about 2.5GHz and it requires about 20 channels. Several options were evaluated based on key expectations for this upgrade.

A partial trade study comparison chart is shown in Table 6. A Keysight S-Series scope was chosen as the best option for this upgrade.

Rank 1-10	Run without Human HW changes	Stable time base	Analog Bandwidth (>2.5Ghz)	Sample rate (10GS/sec min)	Temporal range 1-200ns at full Samp/sec	Vertical multiplexing on at least 2 (max 6) of ANY of the channels	cross time to NIF by better than 50ps	150v Maximum usable voltage (rank 8 with variable Atten)	Over Voltage Survivability (>8v - 1Kv @20ns) 6 = French clipper circuit required 5 = Fixed atten + clipper	minimum voltage able to record is 15mV (with SNR greater than 3x)	Vmin with 1.25v Scale <5mv, Single shot dynamic Range (ENOB = 8)	Easily serviceable	Direct acces to Raw Data	Calibration to better than 1.5%	budget	rack space (10/(#U/chnl cnt))	Rack heat load (1/kW)	Minimize complexity	Does not require software effort	Total
Key Expectation Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8, 3**	**8, 3**	**9, 3**	**10, 3**	**11**	**12**	**13**	**14**					
weight (1-10)	**8**	**9**	**10**	**10**	**10**	**10**	**10**	**10**	**9**	**8**	**10**	**7**	**10**	**8**	**8**	**0.2**	**3**	**5**	**3**	
Keysight scope (2.5Ghz)	8	9	8	9	10	9	10	8	6	10	**7.4**	8	**7**	10	9	5.714	2.67	8	2	1226
Keysight scope (4 Ghz)	8	9	10	9	10	9	10	8	6	10	**7.2**	8	**7**	10	8	5.714	2.67	8	2	**1236**
Tek scope, coax (requires vertical multiplexing all channels)	8	9	10	9	10	**5**	10	8	6	10	**5.6**	8	10	10	3	2.857	3.64	8	8	**1190**
12Ghz Tek scope, MZ	10	8	11	11	10	10	10	10	10	**0**	**8.7**	5	10	5	**2**	0.179	1.33	**1**	5	**1164**
Digtzr card, 3slot PXIe, NI (requires vertical multiplexing all channels)	8	8	9	10	10	**1**	**4**	8	6	10	**6**	8	10	9	**1**	8.333	11.1	5	2	1052
Pizza box, GreenField	8		9	9	8	9	7	8	5	10	10	5	10	5	3	5	10	8	5	1074
Digtzr card, PCIe, KeySight	8	9	10	9	10	9	10	8	6	10	**7.2**	8		10		28.33	4	8	2	**1111**
FTD10000	8	**3**	10	10	**6**	7	7	8	10	10	**11.2**	**1**	10	**3**	**1**	0.333	8.33	8	10	1087

Table 6. Trade of Digitizers for use in the Lower Dante Upgrade

5. CONCLUSIONS

The primary objective of this analysis was to develop a flexible digitizer implementation that will save rack space provide a standard architecture for future diagnostics while maintaining all the current performance capabilities. This can be achieved by the use of three all digital architectures based primarily on two parameters, bandwidth and channel count. The largest benefits are seen by removing vacuum tube based digitizers. The use of channel input circuits (protection and/or signal modification) is needed and will be implemented to maintain the current reliability standard and allow for the transition away from CRT based oscilloscopes.

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